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Water consumption in solar parabolic trough plants: review and analysis of the southern Spain case

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ABSTRACT

The purpose of this paper is to highlight water consumption as a key design parameter in determining the most convenient cooling system and selecting the most appropriate location for Solar Parabolic Trough (SPT) plants. Considering the importance of water in guaranteeing environmental sustainability, a review of water consumption parameters is presented, and water consumption in the SPT plants that are in the planning stages for southern Spain are analyzed as examples. The selected region for the present study, is exposed to high horizontal solar irradiance, undergoes large seasonal weather fluctuations (prolonged droughts) and is located far from the coast (determining the site's topography and soil availability). These characteristics demonstrate that water consumption is one of the decisive factors for the construction of new solar plants in similar locations worldwide, in addition to other considerations such as capital cost or plant efficiency. Currently, most SPT plants are based on the Rankine cycle via a conventional steam turbine generator, which implies the requirement of a cooling system using water. In this paper, all current cooling technologies are reviewed and the required water consumption is analyzed. The impact of plant consumption on the area of SPT plant location is analyzed as well. This paper also discusses the socio-economics and environmental effects of an implemented cooling system. In addition, this paper presents different technical alternatives for minimizing water consumption for cooling and the effects thereof on the rest of the key parameters in the development and construction of a new SPT plant.

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1. Introduction

The aim of this article is to review and highlight importance of water consumption in a Solar Parabolic Trough (SPT) along with other parameters such as technology, economical investments and

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Nomenclature

DNI	Direct Normal Irradiance
HTF	Heat Transfer Fluid
IC	Investment Costs
LCOE	Levelized Cost of Energy
NPV	Net Present Value
OC	Operation Costs
SPT	Solar Parabolic Trough

Symbols

C_e	Specific heat capacity of air (kJ/kgK)
C_v	Latent heat of water vaporization (kJ/kg)
C_w	Specific heat capacity of water (kJ/kgK)
m_w	Mass flow of evaporated water (kg/s)
V_a	Volumetric flow of air put into circulation (m^3/s)
V_w	Volumetric flow of evaporated water (m^3/s)
Q_t	Total power heat dissipated (kW)
Q_w	Dissipated thermal power, absorbed by the evaporation of water evaporation process (kW)
ρ_a	Air density (kg/m^3)
ρ_w	Water density (kg/m^3)
ΔT	Temperature change experienced as a result of air circulation (°C)

reduction in Greenhouse Gas (GHG) emissions. All of these aspects must be identified as clear constraints during the decision stages before, during and after the development and implementation of any new SPT power plant. The beneficial effects of renewable energy in terms of reducing GHG emissions has been extensively investigated [1]. However, limited studies have focused on other environmental parameters such as the one discussed in this paper: water consumption and usage in certain areas that can be affected by power plants based on solar energy.

In fact, plant location, cooling system size and technology underlying a new SPT power plant should be evaluated during the design, sizing and development phases of a project because these parameters have an effect on water consumption and thereby on the environment. Before the implementation of a SPT plant in a selected location, it should be considered that local water resources are in use for human consumption, leisure, industry and agriculture. The implementation of a new SPT plant will be an additional drain that could harm the resources commonly used for these pre-existing activities, placing the sustainability of the local area at risk. From technological point of view, cooling system is a crucial component of water consumption in a SPT plant. However, the technology used for electrical power production will also affect water consumption during the plant life cycle. This paper reviews Rankine technology plants because they are the most common type of SPT power plant constructed and under construction.

To analyze the water problem, this study will use the SPT power plant construction projects in southern Spain [2] as a reference, where water consumption represents a significant problem due to resource scarcity. The main objective of these projects has been, according to Spanish Government, to promote zero-emissions systems, generally called “green energy” systems, to minimize environmental impacts. The location, Spain, was considered for the case study because of high solar radiation intensity in the area with limited water supply.

Horizontal solar irradiance is the key parameter considered for construction of SPT plants. As indicated by maps of horizontal solar irradiance (Fig. 1) and the locations of existing SPT plants and plants planned for the mid-term (Fig. 2), all of the plants are located in areas of high irradiance. On the other hand, water resources in these areas are critical, a crucial factor for SPT plant development in Spain. Section 2 analyzes the available water resources and the expected impact of the SPT plants in these areas.

As a general example, a typical 50-MWe SPT plant needs a plant layout of approximately 200 ha and an adequate electrical infrastructure. High- and medium-voltage power lines must be located nearby to connect the plant to the distribution network. Soil availability and a uniform orography of the location are critical to maximizing solar irradiation and are directly related to efficiency and improving efficiency and improving economic parameters of the SPT system. Consequently, SPT plants are often located in areas with high solar irradiation where water is a scarce resource. Water consumption is distributed among the different activities in these areas; hence, water resources are in direct competition with other potential uses and activities, such as agriculture, industrial or leisure activities, that may be developed in the same area.

Based on these considerations, this article highlights the importance of using a cooling system technology that reduces water consumption. The paper reviews the most important plants in Spain, used as case studies, and analyzes the fact that power generation must be considered another element of local development and not an activity in competition with other water resource uses.

Spain is in the process of implementing SPT plants as a strategic plan to exploit excellent solar irradiation conditions, especially in the southern part of Spain. In Sections 2 and 3, we describe the current hydrologic status and that expected for upcoming years for the selected areas where the SPT plants will be located. In Sections 4 and 5 different cooling systems in SPT plants using Rankine cycles are reviewed and compared. Section 6 analyzes the implementation of SPT plants in Spain and in Section 7 an analysis of plants from the point of view of water consumption is performed.

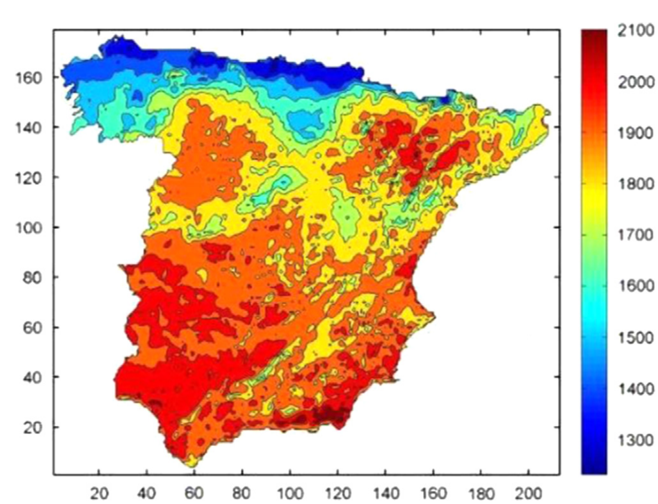

Fig. 1. Horizontal solar irradiance in Spain (kWh/m^2).

Fig. 2. Spanish SPT power plants distribution (Red in service, Yellow under construction and Green as pre-assigned) [2]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Different cooling technologies and their impact on the selected location are analyzed.

2. Water resources in Spain

Fresh and potable water is a limited resource that is affected by global climatic change. Increasing industrial and residential consumption and water pollution reduces the availability of fresh water. High irradiation locations that ensure higher efficiency are best for SPT plants and are areas where water is a scare resource. Water usage for SPT plants is not a crucial issue in regions where there is no conflict between water use activities. For the Spanish case, which is similar to that of regions in North America where SPT plants have a strong presence, water availability is not sufficiently high to supply all of the demands of agricultural, tourist and social uses. Over the past few years, water restrictions have been common in these regions, which implies that water usage for cooling systems in new SPT plants is directly in conflict with other uses. Additionally, for southern Spain, tourism and agriculture are strategic economic sectors.

Spain is a good example within the context outlined above because it is affected by cycles of drainage that have been downward trending over the last few years. Rainfall is decreasing and is expected to decrease dramatically in the next decades. Spanish SPT solar power plants are located in latitudes below 40° north, as shown in Fig. 2. Most of the plants are located on the Guadiana, Guadalquivir and Segura River basins, which are significantly affected by the reduction in water resources due to droughts that regularly affect the Iberian Peninsula (the last one occurred between 2004 and 2007). Because of these trends, water availability will be crucial to these plants. The 2004 report of the European Environmental Agency [3] concluded that Spain and Portugal will be the countries most affected by the near-term climate change within the European Union. Fig. 3 shows the average rainfall for Spain, considered representative of both Spain and Portugal [4], indicating that some areas have low water availability. Fig. 4 shows the forecasted trend of rainfall from 2011 to 2040, taking into consideration the effect of emitted GHGs in Spain. These forecasts correspond to the report by the State Agency of Meteorology of Spain updated for 2009 [5]. Over the last few years, social and political sensitivity for rational use of water has emerged. The assessment of resource availability has led to the regulation of water resource agencies (e.g., the European Commission report on the implementation of the water framework directive [6]) for the use of higher-quality water for drinking and recycled water for industrial and agricultural uses. Different water-quality parameters are controlled according to the specific wastewater treatment method employed; however, the internal processes of SPT plants, such as water required for the Rankine cycle, require a very high water quality. Southern Spain and Portugal are optimal locations for SPT plants in terms of resource availability, but conventional wet cooling technologies require water that is a scarce resource in these regions and will become scarcer according to expert forecasts.

3. Water consumption in SPT plants

Depending on the source, we can classify the water used for cooling towers as follows:

- Natural water: groundwater, reservoirs, rivers or seawater (desalination).
- Industrial or urban wastewater: when a plant is near a city, it may use the industrial and urban wastewater flows with the appropriate purification technology [7], such as a filtration membrane treatment using reverse osmosis [8].

One of the most ambitious projects regarding wastewater treatment is the “Zero Water Discharge” project [9], in which wastewater will be treated and reused in the process using a cascade system and processes depending on the wastewater characteristics. The main drawback of this technology is the increase in both capital and operation costs.

- Industrial wastewater from the cooling water system: The main problems with industrial wastewater are corrosion and inlays.

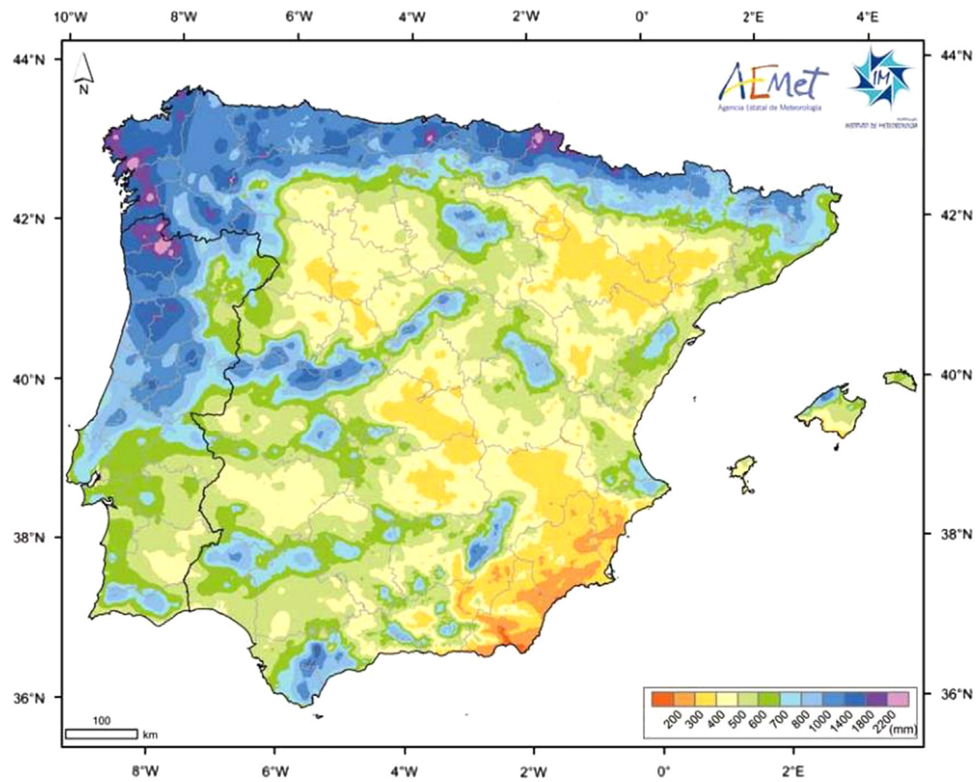

Fig. 3. Rainfall map, Iberian Climate Atlas [4].

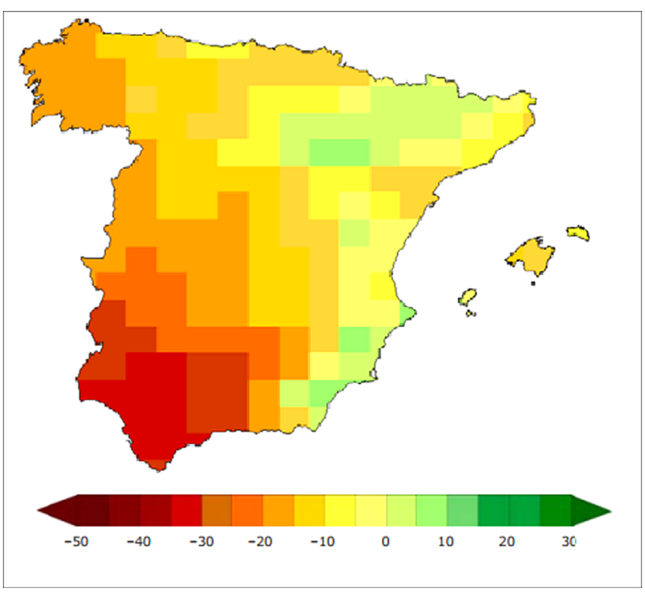

Fig. 4. Rainfall trend expected for the period annual (%) 2011–2040.

Corrosion problems are due to the pH value, which should be between 6.5 and 7 to avoid corrosion processes in the metals used in the SPT. Inlay problems are caused by water hardness, and the effects thereof depend on the thermal conditions of the cooling system. These problems are caused by adding flame-retardant chemicals or lime [10].

Electrical power plants based on SPT technology consume the most water in the cooling systems. Fig. 5 shows a standard central process flow diagram in which the cooling system is highlighted. The cooling system is located in the power block and used for the Rankine cycle. In this case, the cooling system is similar to systems used in conventional power plants, such as coal, natural gas or nuclear plants. The SPT plant has an auxiliary method for pre-heating transfer oil above a certain limit depending on the heat transfer fluid (HTF) that is used. This element is an auxiliary boiler that uses natural gas as fuel for the start-up and stopping processes, with a maximum consumption between 12% and 15% [11].

Most SPT plants that are currently in operation are based on a Rankine cycle via a conventional steam turbine generator, corresponding to the power block in Fig. 5. The outlet steam from the turbine is condensed back into liquid water in the condenser and returned to heat exchangers using feed water pumps that are reused in the cycle. The steam produced in the cooling tower is emitted to the environment. The efficiency is dependent on the turbine exhaust conditions (temperature and pressure).

The heat of water is transferred into the air in the cooling tower through an evaporation process as it flows through the tower and makes contact with the air. Approximately 45% of the total thermal energy is dissipated in the cooling process. To avoid thermal pollution, such as changes in the water temperature around the SPT plant, and damage to the ecosystem's composition, there are two limits to be considered [13]:

- The difference in temperature between the hot water entering and the cold water leaving the system must be less than 3 °C.
- The temperature of the cold water leaving the system in the discharge point must be lower than 30 °C.

The water supply for an SPT plant located in a continental area, often placed far from the coast, comes directly from on-site groundwater wells, rivers or reservoirs nearby. A reference value for the water volume required by a standard SPT plant (50 MWe) using wet cooling technology is 0.89 Hm^3/year [14]. Based on this flow and according to the values reported in the literature [15,16], the water consumption per MWh generated is 3.02 m^3/MWh for

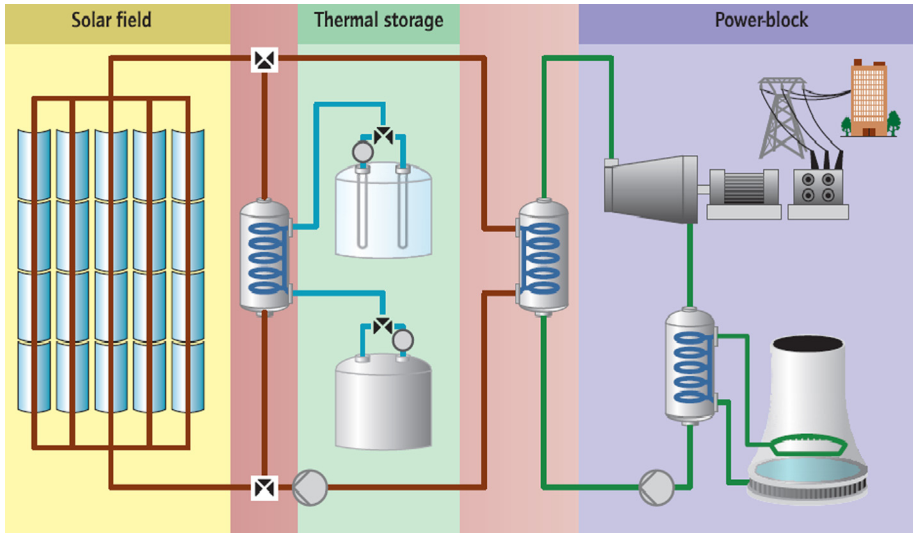

Fig. 5. Schematic of the solar/Rankine parabolic trough system with thermal storage [12].

wet cooling during normal operation. This consumption is distributed as follows:

- Rankine steam cycle consumption $=2.72$ m^3/MWh.
- Cycle makeup $=0.24$ m^3/MWh.
- Mirror washing $=0.06$ m^3/MWh.

The effectiveness of the cooling system will depend on the total performance of the plant, and the total mass flow (kg/s) can be expressed as follows:

$$\textit{Water consumption} = \textit{steam water cycle} + \textit{makeup water} \quad (1)$$

Focusing on the aspects related to the cooling system, the temperature of the cooling water must be as low as possible in the condenser to improve the heat transfer process. The condenser corresponds to the cold focus of the Rankine thermodynamic cycle and should be as large as possible. Most water consumption in the solar plant occurs in the cooling tower system (circulating water flow). The calculations performed for the cooling tower are critical, and the parameters that must considered are

- Rated power of the condenser (equal to tower power, in MW)
- Total water flow (kg/s)
- Evaporating water flow (kg/s)
- Difference between the inlet/outlet water temperatures (°C)
- Latent heat (MW)
- Sensible heat (MW)
- Water flow discharge (kg/s)
- Purge flow (kg/s)
- Specific site conditions

The purge flow depends on the number of recirculation cycles in the cooling tower. A lower amount of gross water is required when there are more recirculation cycles. This recirculation limit is conditioned by the loss of quality in the water, defined by the water conductivity [17].

$$\textit{Maximum number of cycles of recirculation} = \frac{Q_{evaporation}}{Q_{purge}+1} \quad (2)$$

According to this criterion, an increase in cooling water conductivity leads to a renewal of the closed-loop water. The water-quality requirements of a SPT plant that vary depending on its utilization must also be considered:

- Water pre-treated for cooling tower “makeup”,
- Demineralized water for makeup steam cycle,
- Demineralized water for mirror cleaning,
- Water used for auxiliary services.

Some uses require further water treatment to achieve the required quality.

Water is a critical resource in traditional SPT plants using wet cooling systems and is required in many parts of the plants. Different water-quality parameters are required for different uses, including the cooling tower, steam cycle, mirror cleaning and auxiliary services.

4. Cooling system types in SPT plants based on the Rankine cycle

This section describes the cooling technologies most commonly used in SPT plants based on the Rankine cycle. The first consideration is the inlet/outlet temperature of the water cooling condenser. The value must be as low as possible to improve the plant efficiency, referenced as $\Delta T < 10$–15 °C [17]. According to this criterion, SPT plant cooling towers can use the following technologies.

4.1. Wet evaporative cooling system

A general diagram for a wet cooling system is shown in Fig. 6. In this cooling system, heat rejection is performed using a conventional wet cooling tower. The heat removal process occurs within a small volume in the form of sensible heat (10–15%), and the main heat removal process occurs as the latent heat of vaporization (85–90%). This effect is achieved using circulating water due to the evaporation of a small portion of the water in circulation [18,19]. The total heat power dissipated can be estimated as indicated in Eqs. (3)–(5). Eq. (3) explains how heat is dissipated and allows for the determination of the water requirements for a plant.

$$Q_t = Q_a + Q_w \quad (3)$$

$$Q_a = m_a C_e \Delta T \sim 1.2 V_a \Delta T \quad (4)$$

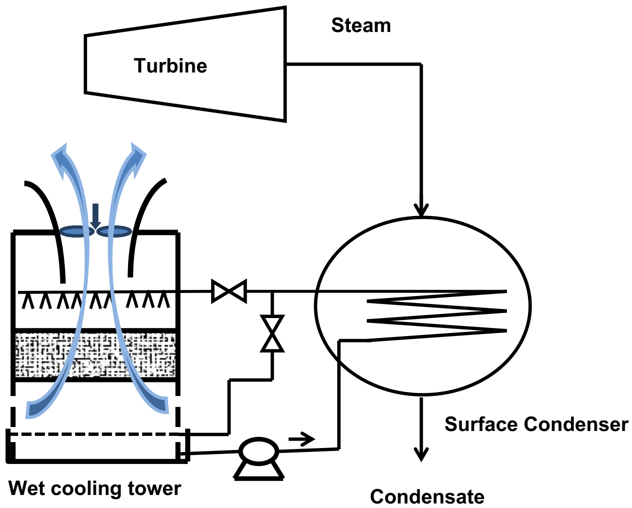

Fig. 6. Wet cooling system diagram.

$$Q_w = m_w C_w \sim 1000 V_w C_v \quad (5)$$

where $m_a = v_a \rho_a$, $m_w = v_w \rho_w$ and m_w is estimated to fall between 1 and 3% of the circulating flow rate.

Fig. 6 shows a wet cooling tower. Cooling towers can be classified as natural draft cooling towers (large structures up to 120 m high) and mechanical draft cooling towers. Mechanical draft cooling towers use large fans to force air through circulated water. These systems have a minor visual impact but are more expensive over the long term due to high maintenance costs. The efficiency of this system can be improved by installing water/air dry heat exchangers behind the evaporation tower facility to reduce the amount of fog produced [20]. This system is particularly useful in cooling processes, with output temperatures required in the summer between 25 °C and 45 °C and those in mostly warm and dry climates reaching temperatures below 25 °C, depending on the wet temperature. The lower cooling limit is fixed by the wet temperature of the environment.

This system is implemented in areas with large water resources (reservoirs, large ponds, etc.) because it is the cheapest and most efficient option besides the direct cooling system.

According to the U.S. Environmental Protection Agency [20], the flow of steam can deposit salts in the areas surrounding a cooling tower, producing corrosion and PM10 (drops Ø < 10 μm) particles that are dangerous to human health, causing diseases such as continuous cough and asthma [21].

There is a small variation in this type of wet cooling system depending on whether a closed-loop evaporative system or an open-loop evaporative cooling system is used. This difference has important implications, for example,

- A closed-loop system reduces the risk of corrosion and scale deposits in the tubes and system equipment.
- The recirculation fluid in a closed-loop system is not exposed to pollution.
- A closed-loop system reduces the risk of legionella proliferation.
- With lower water flow, a closed-loop system reduces the requirement of maintenance operations such as cleaning and disinfection.

4.2. In dry-air cooling

A dry-air cooling system is shown in Fig. 7. In this system, an air exchanger is used for heat rejection; natural draft or forced draft towers can be installed. Heat transfer mainly occurs as sensible heat and its properties depend on weight, specific heat of the air and temperature variation during the cooling process under a constant specific humidity (i.e., the amount of water vapor present in the air). The steam condenses inside fine tubes that are typically arranged in an A-frame configuration and then cooled by air blown across the finned surfaces. The condensation of the steam turbine exhaust plus auxiliary cooling is estimated to represent 5% of the condensing heat load.

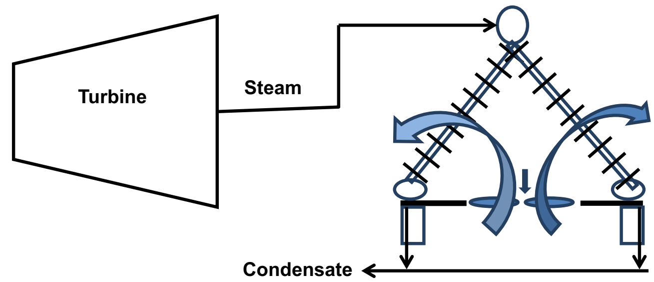

Fig. 7. Dry air cooling system diagram.

$$Q_t = Q_a \quad (6)$$

$$Q_a = m_a C_e \Delta T \sim 1.2 V_a \Delta T \quad (7)$$

The dry cooling system results in 95% reduction in water usage compared to the wet cooling system. The fan consumption required to force the air through the tubes can be minimized by building a natural draft cooling tower; although this type of tower requires a significant initial investment, it operating and maintenance (O&M) costs. The difference between the average outlet temperature and the air inlet temperature is defined as the "terminal" difference. For this parameter, a value between 7 °C and 8 °C is considered economically feasible [22]. A greater reduction in the outlet cooling tower temperature can be achieved using [23] absorption coolers, which can dissipate more power.

Despite the inefficiencies of dry-cooling systems (discussed in section….), these systems provide environmental benefit when installed in the arid and semi-arid environments with regard to lowering water consumption and using fewer chemicals for the disinfecting and cleaning of hydraulic circuits and for waste treatment. Ivanpah 1, 2 and 3 plants in the Mojave Desert (California) are projects which demonstrate the successful implementation of this system

4.3. Indirect dry cooling system (Heller type)

A Heller cooling system is shown in Fig. 8 [24]. The Heller system is an indirect dry-cooling system and is an improved version of the dry-air cooling system described in Section 4.2. The Heller system offers a 1% increase in electricity costs. The main problem with the system is the greater initial capital investment and increased operation costs. In this type of system, thermal power is dissipated by heat exchange in a condenser through a closed-loop water cooling process. The heat that absorbs the water is transferred to the atmosphere through a tube heat exchanger. Air movement can be achieved through a natural or mechanical system. The air is used as a secondary cooling system to the primary cooling circuit consisting of a closed water loop. In the closed water loop, most of the energy is transferred through convection and a small amount is transferred through evaporation, saving 97% of the water used in the wet cooling system. In this system, the flow of cooling water never comes into contact with the cooling air.

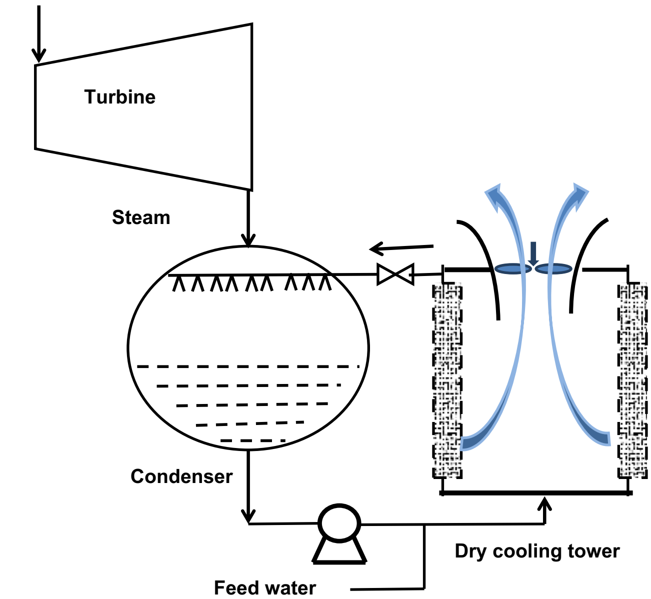

Fig. 8. Heller cooling system diagram.

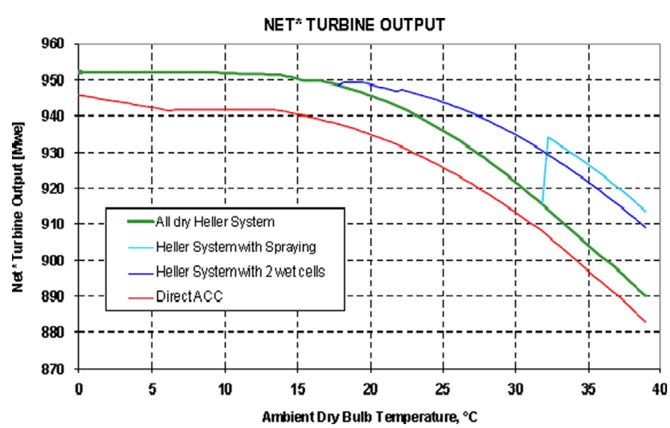

Fig. 9. Behavior of the power output of the turbine depending on the ambient temperature (°C).

There are several types of Heller cooling systems with different structures and element configurations [25]:

- Standard dry-air tower.
- Systems featuring small wet cooling towers used in the summer and laid out in parallel or in series, at a range between 5% and 20% annually.
- Humidifiers (sprays) intake air to the cooling tower (1–3%) in the summer. Adsorption chillers can be used to cool the water circulating through the sprays [26].

The Heller cooling system has different variants, each of which represents an improvement in performance because it increases the dry-bulb temperature, as shown in Fig. 9 for a 900-MWe coal plant. The system can be used over a temperature range of -62 °C to $+60$ °C under extreme conditions. The Heller cooling system has been used for more than 55 years and is still used today in more than 20 countries [27].

A cooling system equipped with a standard Heller air system produces 1.08% more electricity per year than the same plant with a dry-air cooling system, labeled direct ACC in Fig. 9. The different configurations of the Heller system are shown in Fig. 10a, b and c. A natural draft tower is shown, but there is also a forced draft version that is used when the visual impact is more important. A 60-m natural draft tower would not require fans.

The importance of location with respect to plant efficiency should also be considered. For example, a study of an SPT power plant located in the Mojave Desert concluded that the dry cooling system decreases the annual electricity production by approximately 5% and increases the cost of the electrical energy produced by between 7% and 9%. The same system for a similar SPT power plant located in New Mexico only increases the cost of the electric power produced by 2% because the maximum daily temperature is considerably lower.

4.4. Hybrid cooling system (air and evaporative)

A hybrid cooling system involves the operation of two systems in parallel: dry and wet cooling, as shown in Fig. 11. This configuration allows for the type of system in use to be varied depending on the ambient temperature. On warm days, the performance of the hybrid system is enhanced by routing a portion of the steam flow exhaust from the turbine to a separate wet cooling system, which only rejects a portion of the total dissipated heat. A hybrid system uses a fraction of the water used by a traditional wet cooling system, saving up to 80% of the annual water consumption of an evaporative cooling tower. However, a hybrid system requires higher capital and maintenance costs due to the larger number of tubes and systems. This higher material requirement increases the system's cost by approximately 5% compared with that of the wet evaporative system.

This system is useful when the plant has an indirect thermal storage system of molten salts, which is typically composed of 60% $NaNO_3$ and 40% KNO_3, with an equivalent energy storage of 8–9 h. In the summer, the plant may operate with a wet cooling system for a few hours each day. In autumn, winter and spring, the dry cooling system could be used depending on the temperature, and the operation strategy can be optimized by minimizing water consumption. For example, a programming mode of the generation could be adopted based on solar radiation hours and by keeping the plant running at night and during periods of low irradiance [28]. The cost savings associated with lower water flow and lower levels of physical–chemical treatment must be considered [29].

5. Analysis and comparison of the different cooling systems

The advantages of choosing a cooling system depend on the cooling temperatures that can be achieved, and water availability should be considered as a fundamental element of design. Cost-benefit analysis, energy savings and other tangible factors, such as the required maintenance program, are decisive in choosing a cooling system. Other characteristics, such as plant noise levels and their effect on the environment, should also be taken into account. Consequently, the global advantages and disadvantages of each cooling system, including economic, environmental and operational facts, must be considered.

The main parameters of the three cooling systems described (wet, dry and hybrid) are compared in Table 1. In this table, the main considerations for each cooling system with respect to issues regarding water use and advantages and disadvantages are presented and analyzed. In this comparison, the wet cooling system is used as a reference and is thus designated a value of 100% [30]. This system represents the least expensive and most effective option in terms of LCOE and plant energy efficiency because wet systems provide higher efficiency and lower LCOE than all dry systems.

Table 2 shows the main characteristics in terms of both investment and operation for each air system in contrast with a

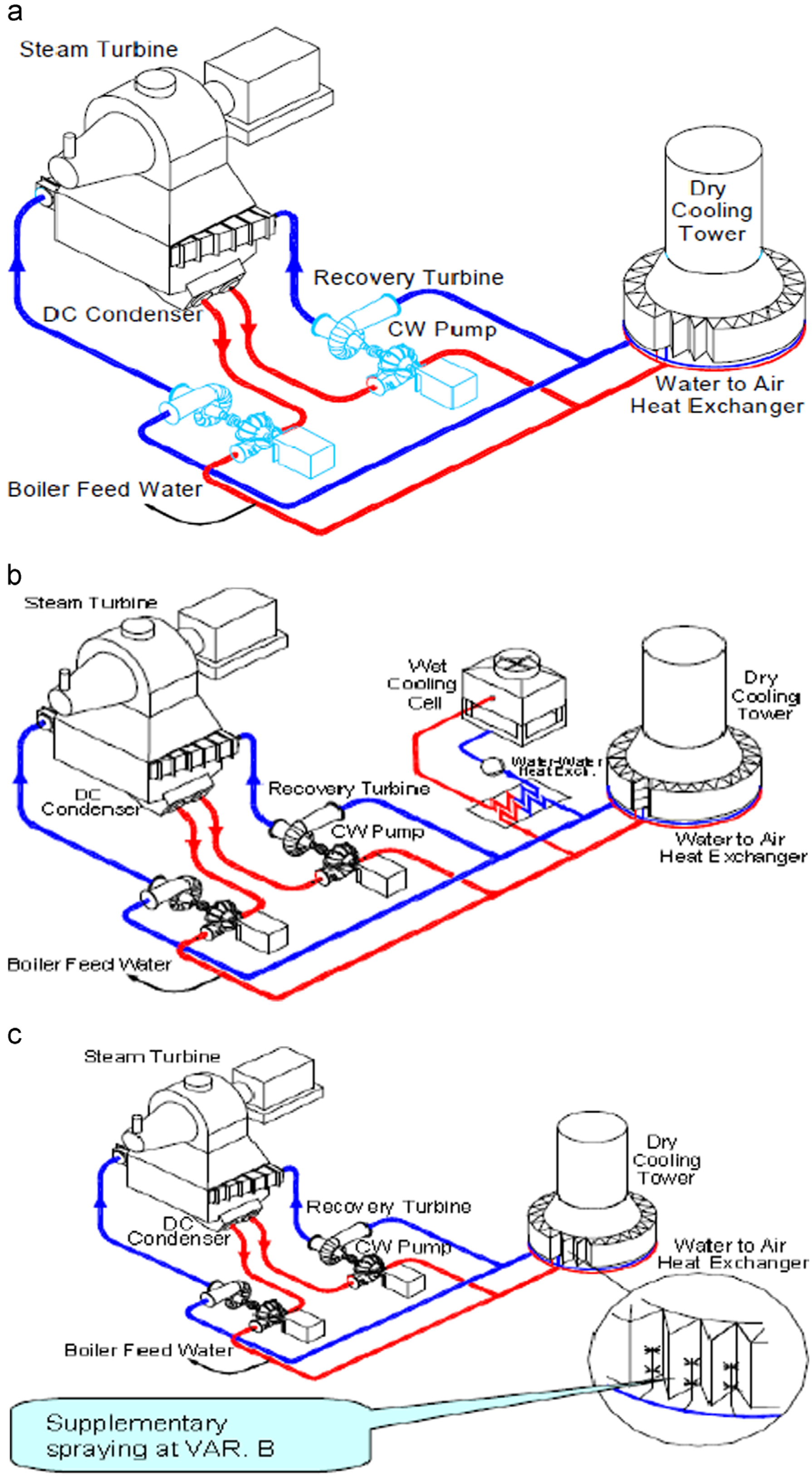

Fig. 10. (a) Heller configuration standard (dry air ACC). (b) Parallel/serial configuration with one or more wet cooling towers. (c) Humidifiers (sprays) where air enters the cooling tower.

wet cooling system. For water consumption, the higher value corresponds to a wet cooling system. Analyzing the main advantages and disadvantages allows for a decision matrix for each cooling system to be defined (see Table 3).

International research estimates a 10% cost penalty and a 7% production penalty in moving from wet to dry cooling for trough systems [31–34]. An alternative hybrid cooling option exists whereby dry cooling is used in the cooler winter months and

wet cooling in summer, or the hottest parts of summer days. According to this research, the production penalty for trough systems is estimated to be only 1% for a 50% saving on water use.

According to an ENREL report [35] in which a molten-salt HTF at a field temperature of 500 °C is assumed for the for the year 2020, tests performed by Enel at the 5-MW Archimedes Plant in Sicily showed that the higher temperature further improves the power cycle efficiency and lowers the storage cost. Direct storage of the HTF in a thermocline system is assumed. Efficiency impacts are calculated as suggested by Kolb [36], and the solar field cost is estimated to be 144 €/m^2. The low cost of storage encourages system designs to incorporate more storage. Operating experience and manufacturing volume are also assumed to push O&M and capital costs down. The solar multiple, calculated as the ratio of solar field thermal energy output to turbine gross thermal energy demand under the designed conditions, ranges from 1.0 to 4.4. The results of this research are presented in Table 4. The results of this study also indicate that economic feasibility of dry systems will increase by the years 2015 and 2020. This demonstrates that dry technology should be considered as a solution for implementation of SPT plants in southern Spain, where water resources are scarce and water use for agricultural is also increasing.

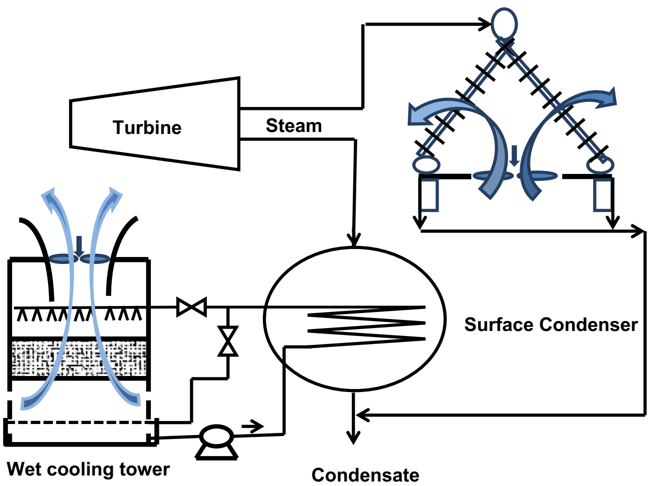

Fig. 11. Hybrid cooling system.

6. The Spain case: implementation of electrical power plants based on SPT technology

In Spain, the Ministry of Industry and Environment has authorized the construction of 40 solar plants, most of which are 50 -MWe SPT plants with cooling systems based on hybrid cooling

Table 1
Comparison main parameters of the three cooling systems (wet, dry and hybrid).

	Wet cooling system	Dry cooling system (AAC and Heller)	Hybrid cooling system
Advantages	Most efficient. Mainly used on hot environments	It involves small volumes of water with little sanitary control and small water discharges	It involves different water volumes of water depending on the season. In general requires less water than the wet cooling system
	Requires little space, with a reduced equipment and a low power consumption in operation	Efficiency is increased in humid and wet environments	The most versatile system. The efficiency can be improved in wet, cold and hot environments
Disadvantages	Involves great volumes of water with sanitary control and great water discharges	Less efficient, depending on the chosen system and its modifications	Intermediate dimensions. If it contains two systems its size is smaller than both of them separately
	Some problems related to steam outlet depending on the season and cold weather	Involves great volumes of air in order to obtain the required cooling power what implies high energy consumption in the fans	–
	–	Great dimensions of the equipment, with a large power consumption	Energy consumption depends on the operation conditions
Use of water	100%	0–5%	20–40%
MWh yearly	100%	92.5%	95.4%
Capital cost	100%	104–109%	103–105%

Table 2
Main characteristics of different cooling systems.

Parameter	Cooling systems			
	Air cooled systems			Wet system
	Indirect natural draft	Indirect mechanical draft	Direct mechanical draft	Circulating evaporative water cooled system
Investment cost	High	High	High	Low
Power consumption	Low	High	Medium-High	Medium
Energy loss	Medium	High	High	No
Water consumption	Low	Low	Low	High
Noise	No	Medium	Medium	Medium
Wind effect	Medium	Medium	Medium	Medium
Recirculation	No	Low-medium	Medium	Medium
Visible plum	No	No	No	Yes
Polluted water discharge	No	No	No	Yes
Maintenance	Low	Medium	Low-medium	High
Plot area	Medium-High	Medium	Medium	Low
Flexibility in site arrangement	Good	Good	Medium	Good
Lifespan of heat exchanger	High (> 30 years)	High (> 30 years)	High (> 30 years)	Low (10 years)

Table 3
Comparison of best and worst cooling solution in terms of different working parameters.

	Installed cost	Operational costs	Parasitic loads	Effective cooling in arid climates	water consumption	Cooling tower blowdown pond
Best	Wet cooling	Dry cooling	Wet cooling	Wet cooling/hybrid cooling	Dry cooling	Dry cooling
Worst	Hybrid cooling	Wet cooling/hybrid cooling	Dry Cooling	Dry Cooling	Wet cooling	Wet cooling/hybrid cooling

Table 4
Analysis of design, cost and performance parameters of cooling systems in the 2020 horizon.

Year	2010	2010	2015	2015	2020
Design Inputs					
Turbine power (gross/net) [MWe]	111/100	110/100	280/250	110/100	280/250
High Temperature Fluid	Syntetic oil	Syntetic oil	Syntetic oil	Salt	Salt
Solar field temperature (°C)	391	391	391	540	500
Solar multiple	1.3	2.0	2.0	2.0	2.8
Thermal storage hours	0	6	6	6	12
Cost and performance inputs					
System availability	94%	94%	96%	96%	96%
Turbine efficiency/cooling method	0.377/wet	0.377/wet	0.356/dry	0.379/dry	0.397/dry
Collector reflectance	0.935	0.935	0.95	0.95	0.95
Solar field [€/m^2]	223	223	186	186	144
HTF field [€/m^2]	68	68	68	38	38
Thermal storage (€/kWh-t)	–	61	61	38	19
Power block (€/kWe-gross)	712	712	663	864	663
O&M (€/kW-year)	53	53	45	45	34
Cost and Performance Outputs					
Capacity factor	26%	41%	43%	43%	60%
Installed cost (€/W)	3.5	6.1	6.0	5.0	4.9
LCOE (cent €/kWh, real)	13.1	13.6	12.5	10.8	7.5

towers with air flow induced fans. As mentioned in the introduction and shown in Fig. 2, most of these plants are located in the southern part of the peninsula, where solar irradiation is high and each plant can be in operation for more than 3000 h/year. These plants use thermal storage in two tanks of molten salts. In the above-mentioned regions, the average annual precipitation was 427 mm for the period from 1971 to 2009 with a declining trend in the medium term.

As an example of the water availability in that area, we can consider the plants completed for drought mitigation in the different watersheds and how the plants use their infrastructure to transfer water between them according to their hydro plan. Some possible management measures were taken in these areas, and some of the projected SPT plants in Southern Spain are based on a hybrid cooling system to minimize the impact on water resources. However, these measures may not be enough to guarantee water availability in this location considering the climatic conditions in the coming years. The water availability may not be sufficient to satisfy the total water demand required from all potential consumers, including the power plant, agriculture, urban uses and leisure. The agricultural sector in Spain has increased its global economic impact over the last few years by increasing exports. According to Spanish Government data for August 2013, vegetable exports have increased by 21.5% compared with 2012 exports, and fruits exports have increased by 10.5% [37]. Most production occurs in southern Spain, where water resources are scarce and in competition with SPT plants, making reducing water consumption a strategic factor for these plants.

No river in the upstream or downstream zone in Spain has a volume flow rate high enough for use in a cooling system or wet cooling tower, which represents the most efficient and cheapest technology of a typical SPT plant. In fact, only the power plants located near the coast use this cooling system using seawater in the cooling process. When using seawater, other costs associated with water salinity that affect the cooling systems should also be considered. According to research conducted by Abdel-Latif [38], who presented a simulation of the Andasol plant in Spain to compare the different economic parameters of wet and dry cooling systems, the production and cost penalty are in accordance with those presented by IEA (main results are presented in Table 5) [31–34].

Table 5
Simulation and comparison of Spanish Andasol plant for wet and dry cooling systems.

General Information		
Number of loops	156	
Effective collector area [m^2]	510,12	
Direct normal irradiance (DNI) [kWh/m^2/year]	2052	
Comparison element		
	Wet	Dry
Energy field [MWh/year]	134,715.8	126,184.27
Capacity factor [%]	31.709.968	28.8091941
Thermal output of solar field [MWh/year]	442,908.3	458,833.01
Economic results		
Internal return rate (IRR) on Equity [%]	9.69	7.28
Net present value (NPV) [€]	109.11	59.32
Payback period [years]	12.35	13.96
Discounted payback period [years]	15.88	20.77
Total incremental costs [€]	262,474,023	280,190,787
Minimum average debt service coverage ratio	1.01	0.91
Required LCOE tariff [€/kWh]	0.301	0.341
Incremental LCOE [€/kWh]	0.152	0.179
Calculation of LCOE		
Levelized electricity costs (LCOE) [€/kWh]	0.2024	0.2293
Total investment costs (IC) [€]	274,259,498	282,859,352
Annuity of IC	0.0782	0.0782
NPV of operation costs (OC) [€]	74,320,528	75,473,190
Annuity of OC	0.0782	0.0782

Most of the current solar plants located in southern Spain are far from the coast, where there are greater limitations on the required energy for the cooling systems, including on electricity

generation [39–41]. The cooling process is performed in a closed loop through mechanical hybrid cooling towers that are induced or backflow forced and are formed by a set of equal modules, each with its own fan. The number of towers is based on the required circulating flow (m^3/h), dissipated power (kW) and evaporated flow (l/s). The temperature of the cooling water is controlled by regulating the fan speed in the tower.

The design and location of generation plants in the interior of the South Iberian Peninsula can address problem related to the heat of condensation evacuation in the cooling tower circuit. This exhaust heat will increase as the installed power capacity rises in the area, especially in those systems that use the Rankine cycle to generate electricity, therefore directly affecting the water requirements.

In this case study, the special weather conditions in the area of study, which are partly caused by the Mediterranean climate, must be considered. Thus, the choice of cooling system has a considerable economic value that is greater than the sum of each SPT plant's component costs, making a detailed consideration necessary when assessing the total generation plant cost of a project and its future amortization costs. In the implementation project plan of SPT plants in the south of Spain, the environmental impact of water consumption was carefully considered because water consumption is a very sensitive problem in Spanish society. Although projects for the new installation of SPT plants in southern Spain include additional measures that optimize water consumption in the SPT plant cooling systems, such as cooling systems operating in a closed loop, there are technological solutions used in other parts of the world that minimize water consumption to an even greater extent.

As a concrete example of the conflicts arising from the use of water resources, for a plant that uses water from a declared “overexploited” aquifer, according to the mandatory environmental impact report [42], the approval of project viability will be given provided that “the rights of irrigation of the agricultural area affected” equivalent to the water needs of the generation plant to be built are obtained, changing the land-use type to dry land.

Although this solution may be technologically feasible and adequate, there is a transfer of resources from one activity, agricultural use, to a different use, energy production. The optimal solution from an economic development point of view is the coexistence of both activities. For instance, A study conducted at University of Castilla-La Mancha, a region where many SPT plants are located, concluded that for this region, the volume of labor required for a crop that requires irrigation is seven times higher than the labor required for a crop using dry land for the same surface area, implying the development of livestock production in addition to agro-food industries, machinery, etc. [43]. Thus, reducing water consumption in SPT plants may allow both activities to be maintained, implying global economic and social benefits for the plant location.

The factors shown in Tables 1–3 and Fig. 12 clearly demonstrate that the most sustainable cooling system from an environmental point of view for the SPT plants in southern Spain would be a 100% dry-air system or a Heller's spray system. Although dry air represents a cost increase between 4% and 9% and decreases the annual amount of energy produced, 3% less than that generated by a hybrid system, it offers the lowest water consumption. The use of this technology is endorsed by previous studies [44], offering a significant increase in the performance of the Rankine cycle cooling systems using air and improvements, such as changes in the geometry of the heat exchangers. Fig. 12 shows the water consumption of the two dry cooling systems, the dry-air system and the Heller system, described in Sections 4.2 and 4.3 [27].

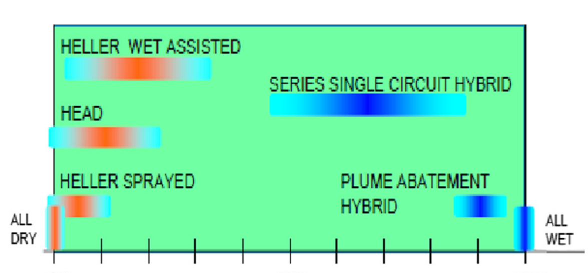

Fig. 12. Yearly water consumption according to the different cooling systems.

7. Alternatives and technological improvements of the state-of-the-art cooling system

In this section, new technologies that can reduce water consumption in SPT plants are discussed and evaluated when the available water resources are shared with other uses, such as park irrigation, agriculture and tourism businesses, although the water quality requirements can vary with use. Some of these technologies have already been tested in other fields.

The combination of the Rankine/Kalina cycles in SPTs uses a mixture of water and ammonia [45] as the heat transfer fluid. Fig. 13 depicts the temperature profile in the condenser. The profile of the water-ammonia mixture temperature is not linear due to the variable nature of the heat evacuation temperature. The Rankine–Kalina cycle increases the power output and is more efficient than the Rankine cycle.

The use of traditional and modern construction methods in developing cooling air systems, where air passes through a water curtain, allows for the air-flow temperature to be lower than the temperature of the surrounding ambient air. Another method may use an underground piping system surrounded by 0.5 m of insulation. The structure is enclosed by a 2.5-m-thick layer, using gravel, grit or sand to reduce the effect of a heat source on the temperature in the subsoil. The soil is watered to maintain the required moisture levels. Heat supply and extraction occur in different horizontal storage layers using parallel pipes [46].

Fig. 14 shows the ambient and soil hourly temperatures at different depths for watered and non-watered systems. The highest registered temperature for the soils without gravel and no watering was 34 °C, whereas the temperature for soils with gravel and watered to maintain the level of moisture was 23 °C.

Generally, technologies that minimize water consumption are more expensive because they require larger equipment and structures to maintain the process performance within acceptable ranges and involve a decrease in the return of investment.

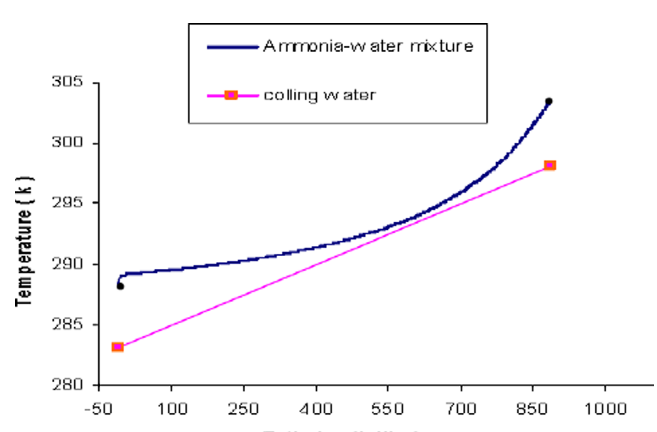

Fig. 13. Diagram of the heat exchange that takes place in the condenser.

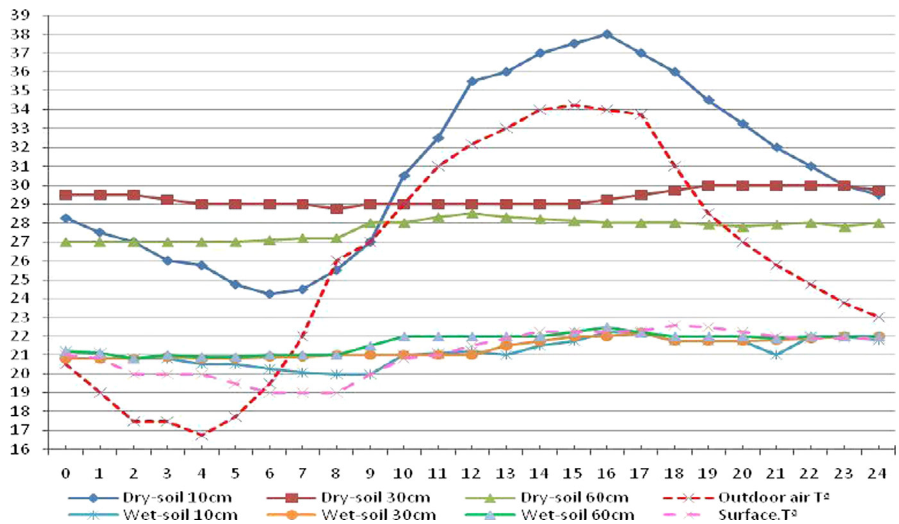

Fig. 14. Evolution of the soil and atmospheric temperature at different depths (August).

However, considering the scale of these systems, an increase in plant size can compensate for the above-mentioned additional costs, especially due to a reduction in operation and maintenance costs. Because of this economy of scale, doubling the electrical plant capacity (MWe) may save between 12% and 14% of the invested capital [47]. Analyzing and optimizing variables such as plant size or investment cost materials for the production of renewable energy can lead to attractive return of investment rates that will ensure the construction of more efficient and technologically advanced plants [48].

Another way to minimize water consumption is to implement technologies for combined generation of electrical power with heating and cooling generation via tri-generation [48–51].

8. Conclusions

This paper summarizes the problems associated with cooling systems in SPT solar plants located in areas with high solar irradiation where water is a scarce resource. As a worldwide reference case, the implementation plan of SPT power plants in Spain is analyzed. It is found that even when using innovations such as the solar energy-powered Rankine cycle for combined power and heat generation using supercritical carbon dioxide [48] intended to improve the Rankine cycle efficiency and CO_2 reduction, water consumption is not considered to be a key parameter, even when these technologies could offer a significant decrease in the water consumed by cooling systems.

Reducing CO_2 emissions and thus preventing climate change is a priority, but the on-site effects of the proposed technologies (such as water availability for irrigation or human consumption) and their environmental impacts must also be considered. Water conservation is crucial to achieve environmental sustainability and should be given priority in similar way as energy efficiency or GHG emission reduction policies.

Considering the large number of solar plants located in southern Spain and the precipitation forecasts for the next few decades, the amount of water needed for cooling solar power plants and the appropriate technology for minimizing its consumption is at least as important in the SPT plant design phase as other aspects such as energy efficiency, location and operation and maintenance costs. In this field, substantial improvements are gained by using proven technologies that minimize water consumption in these types of plants. Different air cooling systems result in a smaller impact on the environment through the responsible use of natural resources, although the use of these systems entails disadvantages such as the additional costs arising from larger facilities and major auxiliary systems' energy consumption. This paper shows that these systems are clearly strengthened by the reduction in the consumption of water, a resource that is increasingly valuable and necessary for life and economic development. The controversy surrounding new solar projects involving the exploitation of thermal solar energy using SPT in southern Spain is a good indication of the complexity involved in choosing a new energy model.

As demonstrated in this paper, two of the penalties associated with using new technologies such as dry-air system or a Heller's spray system etc. for SPT plants are the higher investment and project's lifetime cost and small reduction in plant's yearly power production. However, these impacts should be part of our commitment to sustainability. Research work in this area is directed towards reducing system cost and enhancing its performance globally. Other factors that can be considered in air cooling system technologies are related to the availability of the base resources and their low environmental pollution. Using air cooling systems could lead to an increase in power generation in the arid or semi-arid and sparsely populated areas where SPT plants can be located due to the plant's low water consumption. Moreover, using air systems could lead to a reduction in environmental impact, a crucial issue for future SPT plants project development.

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